Induced magnetic moment of V atoms in ultra-thin epitaxial V/Gd bilayers

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Magnetic properties of vanadium were so far a subject of many studies, both theoretical and experimental. Especially a lot of theoretical and experimental effort during the last few years has been devoted to investigation of Fe/V thin films and superlattices using different techniques like SQUID, CEMS or PNR [1-3]

Results of recent theoretical and experimental papers concerning Fe/V [*eg*.4,5] clearly show an induced magnetic moment in V with antiferromagnetic alignment of V and Fe moments in neighbouring layers. However there exists a discrepancy concerning the range of polarization in V between theory and experiment. Theoretical papers *eg.* [6] for Fe/V system all show strong and short range magnetic polarisation in vanadium, where magnetic moments are localized mostly at the interface vanadium atoms. In [6] using FP-LMTO method induced vanadium magnetic moment of 0.93 μ_B/at only for the interface atoms with simultaneous reduction of Fe magnetic moment in the vicinity of vanadium was theoretically predicted. However in the experimental papers on Fe/V system [7, 8] the existence of induced magnetic moments in V atoms measured by XMCD was reported at the distance up to 4 monolayers from Fe/V interface. In recent XMCD measurements performed at $L_{2,3}$ edges of Fe and V for Fe/V/Fe trilayers [9] a short range polarization was concluded from the signal saturation above 3 ML of V.

However experimentally determined values of V induced moments differ considerably between Fe/V/Fe trilayer and epitaxial Fe/V multilayer. For trilayers [10] a V magnetic moment of 0.5 μ_B/atom was determined and a moment of 0.9 μ_B/atom for Fe/V multilayer was reported. This difference can be explained by the theoretical *ab initio* calculations carried out by Coehoorn [11] showing that an induced magnetic moment of V atom depends on the number of Fe nearest neighbours in its vicinity what is closely related to interdiffusion at the interfaces. The influence of the interface roughness and interdiffusion processes on the enhancement of V polarisation was clearly shown in the case of Fe/V/Fe trilayers deposited at different temperatures [12]. The magnitude of the induced V moment increased by a factor of two upon changing the deposition temperature from 300 K to 600 K.

To the best of our knowledge up to now there was no research of induced magnetism at the interfaces between rare-earths (RE) and 3d non-magnetic metals. For our study we have chosen a system with gadolinium Gd (high magnetic moment per atom, small crystal field anisotropy effects) and vanadium V (to compare with thoroughly studied Fe/V system) which has also this advantage that it can be grown epitaxially in the form of V(110)/Gd(0001) bilayer.

The ultra-thin epitaxial V/Gd bilayers were grown using MBE at a vacuum level of the order of 10^{-10} Torr. In order to achieve epitaxial growth a sapphire substrate with orientation (11-20) and a Mo buffer layer of 20 nm were used. The V layer was grown on the Mo(110) buffer. Samples with V thickness of 5, 8, 10 and 12 monolayers were grown. Above the V layer a 20 ML Gd thin film was deposited. The Al cover layer of about 100 Å was used for protection against oxidation. All the materials were evaporated from electron guns. Deposition rate during growth process was kept at a level of 0.5 Å/s. The Mo buffer layer was deposited at the temperature above 1000°C in order to obtain optimal crystalline structure and minimum surface roughness. The V layers deposition process was preformed at 700°C and Gd was deposited at room temperature. The resulting sample structure was Al_2O_3/Mo/V/Gd/Al. The quality of the interfaces and the crystallographic orientation were investigated in-situ by 12 kV Reflected High Energy Electron Diffraction (RHEED). Auger spectroscopy (AES) was carried out also in-situ to check the chemical composition and any surface contamination of the deposited metallic layers. The X-ray reflectivity measurements using synchrotron radiation (it was necessary due to limited thickness of bilayers) were performed at room temperature at W 1.1 station at HASYLAB in Hamburg, using a wavelength of 1.24 Å and Q-range from 3.5×10^{-3} to 1.15 $Å^{-1}$. The PNR measurements were carried out on PRISM instrument at Laboratoire Léon-Brillouin, in CEA-Saclay, at the temperature of 5 K and with an external magnetic field of 1.5 T in order to magnetically saturate the samples. The wavelength used was 4.3 Å and the Q-range was 0.005 to 0.07 $Å^{-1}$. The spin-up and spin-down reflectivities (R+, R-) of the four samples with different V thickness were measured.

From the magnetization versus temperature M(T) curves Curie temperature was estimated for each V/Gd bilayer and for a reference sample of pure Gd of the same thickness as in the studied bilayers (in both cases a cover layer of 10 nm Al was deposited on the top of the structure). T_c of all V/Gd bilayers was almost independent on the V thickness (264-269 K) but for Gd reference sample T_c was much lower (205 K). Higher Curie temperature for Gd/V bilayer comparing to Gd thin film of the same thickness strongly suggests the presence of vanadium induced moments in all samples. In order to determine the samples structure the X-ray reflectivity measurements were performed. A wide Q-range, which is accessible with X-rays, offers the possibility of precise determination of the nuclear structure parameters like thickness, density and roughness of each constituent layer. They were determined on the basis of the best fitting of calculated reflectivity values to the experimental data using the SimulReflec software [13] assuming bulk densities for all constituent materials. In the assumed structural model an intermixed layer of Al and Gd was introduced at the interface of Al and Gd layers based on the binary alloys phase diagram.. The experimental X-ray reflectivity curves for V/Gd samples and their fittings for the model with Gd/Al intermixing are presented in Fig. 1.

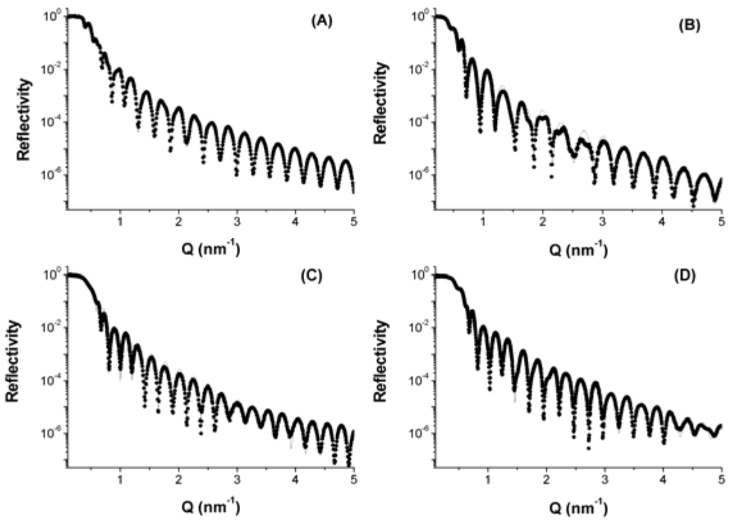

Fig. 1. X-ray reflectivity data for V/Gd bilayers with different vanadium thickness: (A) 12 ML, (B) 10 ML, (C) 8 ML and (D) 5 ML of V, respectively. The solid lines represent the fittings.

At the next stage the PNR measurements were performed at the temperature of 5 K and with an external magnetic field of 1.5 T in order to magnetically saturate the samples. The spin-up and spin-down reflectivities (R+, R-) of the four samples with different V thickness were measured. The structural parameters already found from X-ray reflectivity were used for the fitting of PNR data and the only variable parameters were Gd and V magnetic moments per atom and a direction of the magnetic coupling.

In Fig. 2 the measured and fitted spin dependent neutron reflectivity data are presented for the measured samples. The solid lines represent the fitted spin dependent reflectivity according to the model assuming a mixed AlGd layer. The atomic densities for each layer were assumed to be the bulk ones. For the vanadium layer thickness up to 8 ML the same average V magnetic moment (0.24 μ_B/atom) was found and it increases to about 0.36 μ_B/atom when the V layer thickness reaches the value of 23 Å (sample B) and does not change for higher V thickness. The errors in V moment determination are about ±0.05 μ_B/atom. The magnetic moment of pure Gd layer obtained from the fitting for the studied V/Gd bilayers differs from its bulk value of 7.44 μ_B/atom and varies from 4.7 μ_B/atom to 6.6 μ_B/atom for the samples with 10 ML and 12 ML of V, respectively. It seems that this lower Gd magnetic moment is related to its reduced dimensionality in thin film and interface roughness. For all samples the ferromagnetic alignment of V and Gd moments was found contrarily to the Fe/V system where antiferromagnetic coupling was observed.. The intermixed Al and Gd layers were assumed to be of the type GdAl with a magnetic moment of 0.24 – 0.87 μ_B/atom depending on the sample.

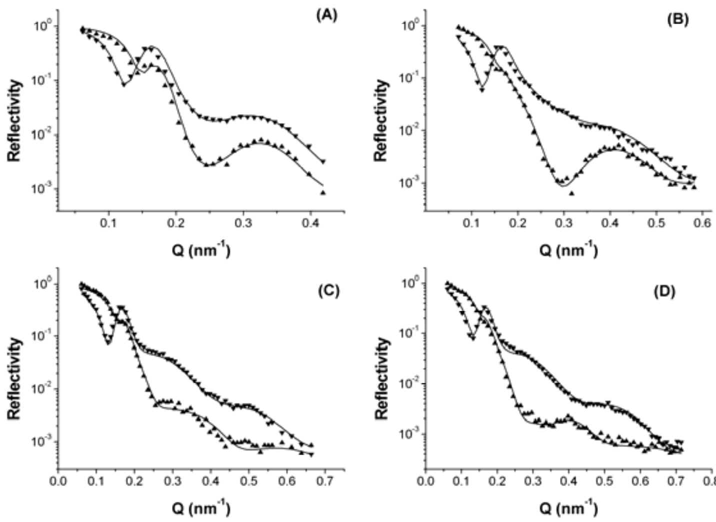

Fig. 2. PNR data for V/Gd bilayers. The solid lines are the least squares model fittings for the samples with (A) 12 ML, (B) 10 ML, (C) 8 ML and (D) 5 ML of V. ▲ denotes spin-up reflectivity, and ▼- spin-down reflectivity.

High quality MBE grown epitaxial bilayers of V/Gd have been fabricated with the V layer thickness varying from 5 to 12 ML keeping Gd thickness constant at 20 ML. The epitaxial relationships of V/Gd correspond to the Nishiyama-Wasserman orientation. X-rays and polarized neutron reflectivity measurements have been used to determine the nuclear and magnetic structure of the films. An induced magnetic moment of V atoms in the range from 0.24 to 0.38 μ_B/atom varying with V thickness has been found. The magnetic moment of the V layer lies in-plane and is aligned ferromagnetically with that of Gd. A reduced magnetic moment of Gd atoms (4.7 – 6.5 μ_B/atom) compared to the bulk value was determined. This effect seems to be connected with the reduced dimensionality of Gd. Vanadium induced moment and its ferromagnetic coupling with Gd results in higher T_c for V/Gd bilayer in comparison to the reference sample of Gd thin film of the same thickness.

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